DOI: 10.1007/s11676-007-0021-0

Carbon storage and flux for alpine tundra ecosystems in Changbai Mountains, Northeast China

WANG Yong-xiang[1], WEI Jing [1*], JIANG Ping[1, 2], WU Gang [1], WANG Hong-chang [1]

[1]*State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, P. R. China*

[2]*Center for Forest Ecology and Forestry Eco-engineering, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, P. R. China*

Abstract: This paper examined the carbon storage and flux of vegetation-litter-soil in alpine tundra ecosystems in Changbai Mountains. Approximately 17251 t·a^{-1} of carbon was yearly stored in the vegetation and 15043.1 t·a^{-1}of carbon flew into soil by litters. The vegetation-litter-soil ecosystem stored 452624 t·a^{-1} of carbon, which was the important CO_2 sink. The net carbon storage was currently 3146 t·a^{-1} in vegetation-litter-soil ecosystem.

Keywords: Carbon Storage, Carbon flux, Alpine tundra

Introduction

Human beings had the most significant impacts on earth system. A series of global environmental problems have been of the great challenge for human beings after 20th century. Especially, global climate change has been a worldwide research topic for a couple of decades (Wei *et al*. 2004). Future temperature changes in high-latitude regions are believed to be larger than those in any other part of the globe. Although such predictions have uncertainties, it is suggested that by 2080, Arctic regions will experience temperature increases of 4–7.5ºC in summer and 2.5–14ºC in winter (Jonasson *et al*., 1999; Hagen *et al*., 2001). Currently, researches on ecosystem pattern and process have greatly progressed at small scale and minitype, short-term bio-phenomenon, but the holistic understanding of earth ecosystem is scant (Yu 2001; Dai *et al*. 2002). Therefore, understanding the response of high-latitude ecosystems to global warming requires more detailed information on vegetation and soil nutrients, because despite the harsh climate, biological productivity is often limited by nutrient availability (Benjamin *et al*. 2004). Carbon cycling of ecosystems is an important part of sophisticated processes of global climate change. Many studies on carbon cycling in terrestrial forest ecosystems, plain ecosystems, farmland ecosystems and ocean ecosystems were conducted to probe into the action mechanism between vegetation ecosystems and global climate change and to better understand the function and structure of vegetation ecosystems (Frisdli *et al*. 1986; Barnola & Vostok, 1987; Boden *et al*. 1993; Raynaud *et al*. 1993; Zhang *et al*. 1996; Fang & Wei 1998).

Tundra, found solely in the arctic and alpine areas of the north hemisphere, is characterized by gramineous grasses, weeds, low shrubs, mosses and lichens growing on soils with permafrost layers underground. Tundra ecosystem, including arctic, alpine and mountainous tundra, is a mass storage of carbon. This ecosystem is sensitive to warmer and drier climate as predicted by almost all climate change scenarios. The alpine tundra in Changbai Mountains represents the southern limit of eastern tundra in mid-Eurasia. The cold and wet climate conditions determine carbon turnover of tundra ecosystems at a low rate. Therefore, alpine tundra of Changbai Mountains is one of focal ecosystems that are suitable for studying interactions between climate change and ecosystem structure, including its physiognomy and biodiversity.

The aim of this research is to examine carbon dynamics and pools of Changbai alpine tundra in which litter has accumulated. The carbon dynamics within the system were examined, as carbon is regarded as the most component in vegetation succession. To establish a carbon budget and cycling pattern within and between, the soil, litter and plant compartments for a high-middle altitude 303-year-old tundra vegetation, the carbon levels of aboveground, belowground components, litter and soil were measured. This could be to provide information for the effective management of the systems. The applied significance of the work is that annual bio-cycling pattern in tundra ecosystems is important for evaluating sustainable management of carbon source & sink. At the same time, we intend to reveal the mechanism between carbon cycling of alpine tundra and local climate change.

Foundation project: This research was supported by National Natural Science Foundation of China (No: 40473054) and Agricultural Technological Production Translation of Science and Technology of Ministry (No: 05EFN216600446).

Received date: 2006-10-27; Accepted date: 2007-01-07

Electronic supplymentary material is available in the online version of this article at http://dxdoi.org/10.1007/s11676-007-0021-0

Biography: Wang Yong-xiang (1958-), male, Ph.D Candidate, at State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, major in environment management and restoration ecology

*Corresponding author: WEI Jing (E-mail: weijing@rcees.ac.cn; weijingrcees@126.com)

Responsible editor: Chai Ruihai

Materials and methods

Study area

Changbai Mountains lies along the border of China. The altitudinal vegetation zonations on Changbai Mountains include broad-leaved forests, mixed forests, coniferous forests, birch forests, and tundra (Fig. 1). The physiognomy includes mainly volcanic physiognomy, glacier physiognomy and ice edge physiognomy. There are many snow packs on the peak. The alpine tundra on Changbai Mountains is the only arctic vegetation in China. It lies within the geo-position 41º53' and 42º04' North latitude, 127º57' and 128º11' East longitude between 1 950 and 2 690 m amsl and its total area is 15 860 hm^2, in which, the area of vegetation coverage is 15 190 hm^2, accounting for 95.78% of the total alpine tundra area. The mean annual radiation is 506.6 $J{\cdot}cm^{-2}{\cdot}a^{-1}$, the mean annual light time 2 295 h, the mean annual temperature -7.4 ºC , January mean temperature (the coldest month) is -23.8 ºC, July mean temperature (the warmest month) is 8.4 ºC, the highest temperature is 19.2 ºC, and the lowest temperature is -44 ºC, as observed from a meteorological station located at 42º01' N，128º05' E, and 2 623 m amsl. The mean annual rainfall is 900□1340 mm.

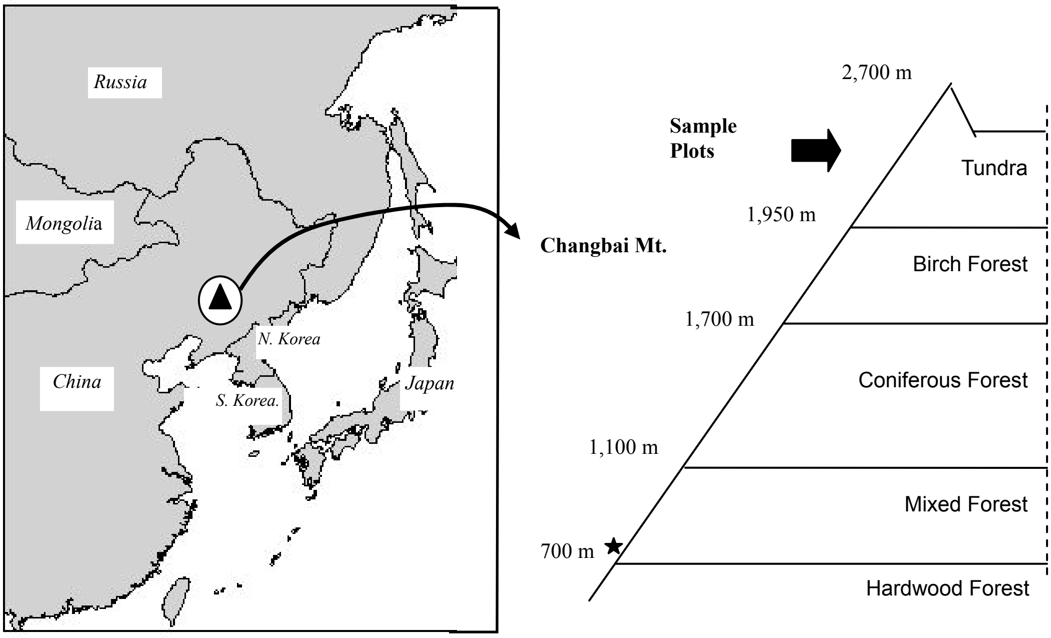

Fig.1 The sketch of Changbai Mountains Nature Reserve, showing main vegetation types and sampling plots in tundra.
The sampling sites were located at the altitude from 1950 to 2650 m. The area of studied tundra is 15195 hm^2, including five vegetation types and five soil types. Vegetation types are Felsenmeer alpine tundra vegetation (FA), Lithic alpine tundra vegetation (LA), Typical alpine tundra vegetation (TA), Meadow alpine tundra vegetation (MA), and Swamp alpine tundra vegetation (SA). Soil types are Cold desert alpine tundra soil (CDS), Lithic alpine tundra soil (LS), Grey alpine tundra soil (GS), Meadow alpine tundra soil (MS), and Peat alpine tundra soil (PS).

Field experiment design and sampling

Sampling collection and measurements were conducted in late July and early August of 2003 and 2004. Four transects were randomly allocated on the representative sites of each vegetation type with similar aboveground conditions, geomorphic and hydrological conditions. The 4 m×4 m plots were systematically set up at 1950, 2050, 2150, 2250, 2350, 2450, 2550, and 2650 m amsl (Fig.1). At each plot, we measured vegetation height, coverage as well as the number of species. The four sub-plots were set up in the core of each plot. Each sub-plot was sized 0.2 m×0.2 m. Plants (including roots) were collected with the harvest method at each sub-plot. Nearly all collected plants were in growing season (the most biomass). The soil bulk density was measured at the depths of 5 and 15 cm, and the data of soil bulk densities, which were adjusted for stone content at each vegetation type. Four soil samples at each depth of 0~10 and 10~20 cm were collected from each profile to analyze inorganic carbon and organic carbon concentrations.

Samples measurements and analysis

The plant and litter samples were weighed by wet weight on the spot. These samples of plants and litter were placed in paper envelopes and dried in the sun. They were oven-dried at 65 ºC upon returning to the laboratory. Dried samples were ground to a fine powder using a ball mill and filtered with 80 griddles and kept for chemical analysis. The soil samples were air-dried and ground and kept for chemical analysis. The total carbon concentration was analyzed by CNS-Analysator LECO SC444; organic carbon was measured by spectrophotometer after digestion with $K_2Cr_2O_7/H_2SO_4$; inorganic carbon was calculated as total carbon minus organic carbon. The analysis of variance (ANOVA) was

performed using SPSS.

Carbon pool and soil respiration

The biomass and productivity (dry weight) of the sub-plots were got through a harvesting method. The biomass and productivity of each vegetation type were inferred according to area of sub-plots and each vegetation type, and then biomass and productivity of tundra vegetation on Changbai Mountains were derived. Using mean values of carbon concentration and biomass, it could determine vegetation and litter pools while soil carbon pool (kg·hm^{-2}) were calculated using the following formula (Guo and Gifford, 2002): P = 100×C×BD×D (1); Where C is carbon concentration converted to g.kg^{-1}; BD is soil bulk density in g.cm^{-3}; D is soil depth in cm. The soil depth measured at this site was 20 cm.

Soil respiration was calculated using the following formula (Fang & Wei, 1998): S_R (g·m^{-2}·yr^{-1}) = $1382.95-203.21\sqrt{27.73-T}$ (2); Where S_R is soil respiration rate (g·m^{-2}·yr^{-1}), T is the mean annual air temperature (^{0}C). The mean annual air temperature was computed from meteorological data collected in alpine tundra on Changbai Mountains Forest Ecosystem Research Station of Chinese Academy of Sciences (Dai *et al*., 2002).

Results and discussion

Carbon storage and flux of vegetation in alpine tundra ecosystem

The carbon storage and flux of vegetation in each vegetation type are summarized in Table 1. Between the two components of vegetation, belowground part has higher biomass than that of aboveground in Felsenmeer alpine tundra vegetation (FA) and Lithic alpine tundra vegetation (LA) while aboveground biomass higher than that of belowground in Typical alpine tundra vegetation (TA), Meadow alpine tundra vegetation (MA) and Swamp alpine tundra vegetation (SA). The carbon flux in SA is the highest while in FA the lowest. But TA has the highest carbon storage, of which is 96.2% of total carbon storage in alpine tundra of Changbai Mountain. This is significantly correlated with the wide distribution of typical alpine tundra and relatively high carbon flux (Dai *et al*., 2002).

Table 1 Carbon storage and flux of vegetation in each vegetation type

Vegetation type	Area (hm^2)	Carbon flux* (t·hm^{-2}·a^{-1})	Annual net productivity of tundra* (t·a^{-1})	Biomass (t·hm^{-2})			Carbon storage (t)
				Aboveground	Belowground	Total	
Felsenmeer alpine tundra vegetation(FA)	85	0.06	5.1	0.02**±0.04	0.04**±0.02	0.06±0.04	5.1
Lithic alpine tundra vegetation (LA)	4160	0.25	1040	0.1±0.03	0.15±0.02	0.25±0.05	1040
Typical alpine tundra vegetation (TA)	10870	1.48	16087.6	1.75±0.15	1.21±0.46	2.96±0.51	32175.2
Meadow alpine tundra vegetation (MA)	65	1.45	94.3	1.77±0.57	1.13±0.78	2.9±0.86	188.3
Swamp alpine tundra vegetation (SA)	15	1.61	24.2	2.38±0.03	0.84±0.01	3.22±0.04	48.3
Total	15195	1.14(ave.)	17251.2	1.17(ave.)	1.04(ave.)	2.21(ave.)	33456.9

Note: Mean value and standard deviation of sub-plots biomass are reported. Values behind ± sign are standard deviation; * data from Dai Limin et al.(2002); ** means that this value is significantly different when p<0.05

Carbon storage and flux of litter in alpine tundra ecosystem

Litter is an essential component of material cycling and energy flowing in forest ecosystem. Study of the litter biomass and its nutrient dynamics play a very important role in estimating the flow of material and energy in vegetation-soil system (Maguire 1994). The alpine tundra vegetation on Changbai Mountains (litter is the main nutrient source of soil nutrient dynamics in natural or non-disturbed ecosystem) grows in bloom due to abundant nutrients of litter in the alpine tundra.

The total carbon storage of litter in alpine tundra on Changbai Mountains is 15 043.1 t, in which TA accounted for 85.1% in carbon storage (Table 2), mainly caused by the very large area of TA and high litter biomass. Moreover, the low air temperature and great wind result in the decrease in the decomposing rate of litter and increase in organic carbon storage when the time passed (Wei *et al*. 2004a). The mean annual biomass of litter in alpine tundra ecosystem on Changbai mountains is 0.99 t·hm^{-2}·a^{-1}, which is close to that of alpine tundra in polar regions (0.9 t·hm^{-2}·a^{-1}) (Liu 2003). Litter biomass in TA and SA is very large mainly due to a high level of vegetation coverage and density. Since the latest volcanic eruption in 1702, according to net productivity, biomass and organic carbon storage of alpine tundra vegetation, organic carbon has being flew into soil at a rate of 15043.1 t·a^{-1} in the form of litter.

Table 2. Carbon storage of litter in each vegetation type

Vegetation type	Area (hm^2)	Litter biomass (t·hm^{-2}·a^{-1})	Carbon storage (t)
FA	85	0.06*	5.1*
LA	4160	0.25*	1040*
TA	10870	1.15	14881.7
MA	65	1.04	135.2
SA	15	1.21	36.3
Total	15195	0.99（average）	15043.1

Note: * inferred from the reference (Fang & Wei 1998)

Carbon storage and flux of soil in alpine tundra ecosystem

According to the characteristics of each soil type of alpine tundra on Changbai Mountains (such as area, soil bulk density etc.), the storage of inorganic carbon, organic carbon, and total carbon were calculated at the depth of 0–20 cm in different soil types. It was evident from table 3 that different soil types had different levels of carbon concentrations, PS>MS>GS>LS>CDS. The surface soil layer at the depth of 0–10 cm contained much more carbon than the sub-surface soil layer at the depth of 10–20 cm. Tundra soil (0–20 cm) on Changbai Mountains contained

452624 t carbon in total, among which organic carbon accounted for 69.9%, inorganic carbon 30.1%, and the surface layer of tundra soil (0−10 cm) contained 58.7% of the total soil carbon. whereas the sub-surface layer (10−20 cm) contained 41.3% of the total soil carbon (Table 3). This research also suggested that soil organic carbon storage was not consistent with the corresponding carbon flux per area at each vegetation type. The direct reason is due to the remarkable differences in species, temperature, and water table in vegetation types (Wei *et al*. 2004; 2004a). However, the indirect reason is possibly that these shrubs and herbs in TA and MA, such as *Dryas octopetala var. asiatica, Carex atrata, Polygonum ochotense*, may allocate more biomass to roots through waxes and lignins which contain more cellulose to synthesize, and more roots, especially fine roots, can fix more carbon (Wu *et al*. 2006).

Table 3. Carbon concentration and storage of soil in each soil type

Soil type	Area (hm^2)	Soil depth (cm)	Inorganic carbon (%)	Organic carbon (%)	Bulk density ($g \cdot cm^{-3}$)	Inorganic carbon storage (t)	Organic carbon storage (t)	Carbon storage (t)
Cold desert alpine tundra soil	85	0~10	$0.29^{*}\pm0.12$	$0.55^{*}\pm0.13$	0.78	340.17	645.15	985.32
		10~20	0.13±0.98	0.45±0.03	0.62	152.49	527.85	680.34
Lithic alpine tundra soil	4160	0~10	0.42±0.32	0.78±1.45	1.05	23412.48	43480.32	66892.8
		10~20	0.13±0.78	0.67±0.14	0.91	7246.72	37348.48	44595.2
Grey alpine tundra soil	10870	0~10	0.53±2.43	0.88±1.78	1.13	73742.08	122439.68	196181.76
		10~20	0.22±0.89	0.79±1.12	1.01	30609.92	109917.44	140527.36
Meadow alpine tundra soil	65	0~10	0.62±0.79	0.96±0.20	1.17	491.66	761.28	1252.94
		10~20	0.31±0.17	0.85±1.15	1.04	245.83	674.05	919.88
Peat alpine tundra soil	15	0~10	0.56±1.05	1.02±1.12	1.36	111.72	203.49	315.21
		10~20	0.34±1.10	1.03±0.12	1.37	68.73	205.49	273.32
Total	15195	0~20	/	/	/	136421.8	316203.23	452624.13

Notes: Mean value and standard deviation of soil carbon concentration and content are reported at different soil depths of each soil type. Values behind ± sign are standard deviation. * means that this value is significantly different when $p<0.05$.

Soil respiration in alpine tundra ecosystem

The process of soil respiration releasing CO_2 to atmosphere is one of the main processes of carbon cycling in ecosystem (Wei *et al*. 2004a). According to formula (2), the alpine tundra on Changbai Mountains released 92.72 $g \cdot m^{-2} \cdot a^{-1}$ of carbon. Plant roots and soil accounted for 1/3 and 2/3 of the total release, respectively. For the total area of alpine tundra, alpine tundra soil on Changbai Mountains released 14105 $t \cdot a^{-1}$ of carbon.

Carbon storage and flux in alpine tundra ecosystem on Changbai Mountains

Approximately 17 251 $t \cdot a^{-1}$ of organic carbon was stored in the alpine tundra ecosystem by plant assimilation yearly and 15043.1 $t \cdot a^{-1}$of organic carbon flew into soil by litters. Soil including plant roots, via soil respiration released 14 105 $t \cdot a^{-1}$ of organic carbon to atmosphere yearly (Fig. 2). The vegetation-litter-soil ecosystem of alpine tundra on Changbai Mountains stored 452 624 t of total carbon, organic carbon of which was 364 713 t, which it agreed with the results of document (Dai *et al*. 2002). After the vegetation was stabilized, the vegetation-litter-soil ecosystem stored 3146 t of total carbon per year.

Conclusions

The storage of soil organic carbon appears to change in vegetation types, although the similarities in soil organic carbon between LA and FA, or among TA, MA, SA would be difficult to anticipate without census information showing the proportionally large number of shrubs and herbs in the community at five vegetation types.

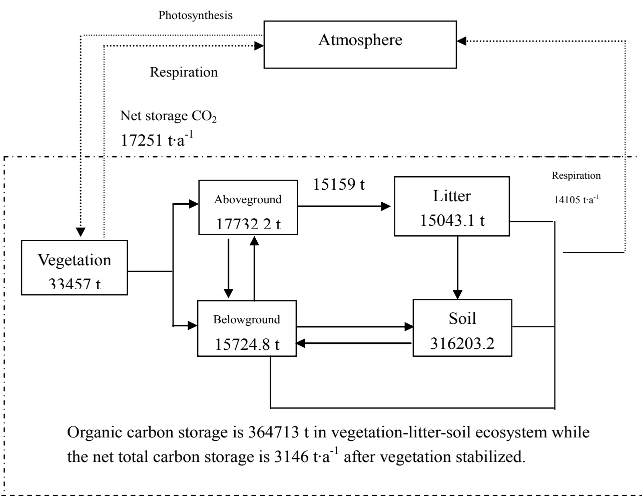

Fig. 2 The sketch of carbon storage and flux in alpine tundra ecosystem on Changbai Mountains

The results showed that the alpine tundra ecosystems on Changbai Mountains was the current CO_2 sink (the net carbon storage of 452624t) and also provided information for the effective carbon management and evaluating sustainability of alpine tundra ecosystems on Changbai Mountains. However, tundra soil respiration was one of the main impact factors that affected carbon source-sink, but surface flow and underwater flushed out parts of carbon from alpine tundra to low-elevation *Betula ermanii* and coniferous forests. The tundra soil respiration in real-time monitoring and flow quantification between different vegetation types and sub-ecosystems and its relation with soil, water, and climate have not been studied and should be the future

innovation points.

Acknowledgements

The study was supported by National Natural Science Foundation of China (No: 40473054) and Agricultural Technological Production Translation of Science and Technology of Ministry (No: 05EFN216600446). We also thank the Forest Ecosystem Research Station of Changbai Mountains, Chinese Academy of Sciences (CAS) for their support of field investigations and experiments.

References

Barnola, J.M. *et al*. 1987. Vostok ice core provides 160000-year record of atmospheric CO_2. *Nature*, **329**:408−414.

Bond, G., Broecker, W., Johnsen, S., *et al*. 1993. Correlations between climate records for North Atlantic sediments and Greenland ice. *Nature*, **365**: 143−147.

Dai Limin, Wu Gang, Zhao Jingzhu, *et al*. 2002. Carbon cycling of alpine tundra ecosystems on Changbai Mountains and its comparison with arctic tundra. *Science in China* (Series D), **45** (10): 903−910 (in Chinese).

Fang Jingyun, Wei Menghua. 1998. The relation between carbon cycling of the Arctic and global changes. *Journal of Environmental Science*, **18** (2): 113−121. (in Chinese)

Friedli, H., Lötscher, H., Oeschger, H., *et al*.1986. Ice core record of the $^{13}C/^{12}C$ ratio of atmospheric CO_2 in the past two centuries. *Nature*, **324**: 237−238.

Guo, LB, Gifford, R.M. 2002. Soil carbon stocks and land use change: a case analysis. *Global Change Biol*., **8**(4): 345−360.

Hagen, J.Q., Jefferies, R., Marchant, H., Nelson, F., Prowse, T., Vaughan, D.G., 2001. Polar regions (11Arctic and Antarctic). In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge: Cambridge University Press, pp 801−841.

Jonasson, S., Michelsen A.; Schmidt I.K., 1999. Coupling of nutrient cycling and carbon dynamics in the Arctic, integration of soil microbial and plant processes. *Appl. Soil Ecol*. **11**(2): 135−146.

Liu Qiang. 2003. Ecological experimental study on the reciprocal decomposition of foliar litter in tropical and subtropical forests o southern China. Guangzhou: South China Institute of Botany, Chinese academy of sciences, Ph.D dissertation: 1−13. (in Chinese)

Maguire, D.A. 1994. Branch mortality and potential litterfall from Douglas-fir trees in stands of varying density. *Forest Ecology and Management*. **70**: 41−53.

Raynaud, D., Jouzel, J., Barnola, M., *et al*. 1993. The ice record of greenhouse gases. *Science*, **259**: 926–934.

Tutner, B.L., Baxter, R., Mahieu, N., Sjögersten, S., Whitton, B.A. 2004. Phosphorus compounds in subarctic Fennoscandian soils at the mountain birch (*Betula pubescens*)-tundra ecotone. *Soil Biol. Biochem*. **36**(5): 815−823.

Wei Jing, Wu Gang, Deng Hongbing, *et al*. 2004. Spatial pattern of soil carbon and nutrient storage at the alpine tundra ecosystem of Changbai Mountain. *Journal of Forestry Research*, **15**(4):249−254.

Wei Jing, Wu Gang, Deng Hongbing. 2004a. Researches on nutrient return of litterfall in the alpine tundra ecosystem of Changbai Mountains. *Acta Ecologica Sinica*, **24** (10): 1421−1430.

Wu Gang, Wei Jing, Deng Hongbing, Zhao Jingzhu. 2006. Nutrient cycling in an alpine tundra ecosystems on Changbai Mountain, Northeast China. *Applied soil ecology*, **32**: 199−209 (in Chinese).

Yu Guirui. 2001. A conceptual framework and the ecological basis for ecosystem management. *Chinese Journal of Applied Ecology*, **12** (5): 787−794. (in Chinese)

Zhang Yahui, Li Changsheng, Gao Zhenming. 1996. *Element Cycling of Composite Ecosystem.* Beijing: China Environmental Science Press, pp30−59. (in Chinese)